INTERNAL COMBUSTION ENGINE CYLINDER-TO-CYLINDER BALANCING WITH BALANCED AIR-FUEL RATIOS

TECHNICAL FIELD OF THE INVENTION

This invention relates to internal combustion engines, and more particularly to balancing combustion of such engines.

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BACKGROUND OF THE INVENTION

An internal combustion engine operates best when combustion is balanced among its cylinders. However, a number of factors contribute to cylinder-to-cylinder combustion variations, such as mechanical construction of the engine, engine condition, and combustion controls. To compound the problem, each cylinder can be fueled differently and breathe differently from cycle to cycle.

To help reduce cylinder combustion variation, some engine designers have used fuel balancing valves in the fuel lines upstream of the cylinders' fuel injection valves. These valves are used to adjust the fuel delivery to a given cylinder. Conventionally, adjustments are made until the peak firing pressures of all cylinders are equal.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present embodiments and advantages thereof may be acquired by referring to the following description taken in conjunction with the accompanying drawings, in which like reference numbers indicate like features, and wherein:

FIGURE 1 illustrates measured pressure traces for a six-cylinder engine.

FIGURE 2 illustrates simulated pressure traces for a virtual six-cylinder engine.

FIGURE 3 illustrates simulated pressure traces where fuel flow has been adjusted to achieve equal peak firing pressures for all cylinders.

FIGURE 4 illustrates air-fuel ratios for the cylinders of FIGURE 3.

FIGURE 5 illustrates the pressure traces for a simulated six-cylinder engine having equal air-fuel ratios for each cylinder and the cylinders also having varying air manifold pressures.

FIGURE 6 illustrates a method of cylinder-to-cylinder balancing in accordance with the invention.

FIGURE 7 illustrates how the method of FIGURE 6 may be implemented using an interactive computer interface.

DETAILED DESCRIPTION OF THE INVENTION

As indicated in the Background, this invention relates to the problem of balancing combustion in spark ignited internal combustion engines. The problem is particularly evident in large engines, such as the natural gas engines used for industrial applications. However, the same concepts could be applied to any internal combustion engine having more than one cylinder. The invention is appropriate for any spark ignited engine equipped with sensors capable of measuring pressure in each cylinder and devices to adjust fueling to each cylinder independently.

The combustion balance problem may be stated as follows. The combustion event that occurs in one cylinder tends to differ from the combustion event in the other cylinders, even with averaging over many cycles to eliminate cycle-to-cycle variability. The average air flowing into each cylinder often differs from that for the other cylinders, and the fuel flowing into each cylinder differs from that for the other cylinders.

FIGURE 1 illustrates measured pressure traces from a six cylinder engine. Pressure measures are made, using appropriate sensors, within each engine cylinder. Each cylinder's cycle is represented by one pressure trace. More specifically, each trace represents average cylinder pressure over 50 cycles, and each is plotted against crank angle, referred to the cylinder's bottom dead center (BDC), that is, the instant at which the piston reaches the point in its travel closest to the crankshaft.

The traces of FIGURE 1 show differences in the buildup of pressure between 0 degrees and 180 degrees of crank rotation (pre-ignition) and further differences in the buildup of pressure after ignition to the point of maximum pressure (peak firing pressure).

For a two-stroke engine, the pre-ignition pressure buildup follows the inducing of air through the ports and trapping and compressing a mass of air in the cylinder after the ports close. The differences result from uncontrolled air flow dynamics in air and exhaust manifolds, which strongly influence cylinder air flows. At some point after the ports close, fuel is injected into the cylinder. If, at some finite angle prior to top dead center (TDC), the pressures differ, this implies a difference in the mass of air and fuel trapped in the cylinder.

As a result of combustion imbalance, without corrective action, six different pressure traces occur, implying six different combustion events, some richer than others, some leaner than others. In FIGURE 1, the pressures in different cylinders at 20 degrees before TDC (160 degrees) vary by close to 10% of the average pressure, implying a 10% difference in trapped air mass. If the pressure traces cross each other after ignition, as in FIGURE 1, this indicates that the air-fuel ratio, as well as the trapped air mass, differs among cylinders.

FIGURE 2 illustrates simulated pressure traces for a virtual engine, which exhibits imbalance characteristics similar to those of FIGURE 1. FIGURE 3 illustrates the simulated results of using conventional balancing methods

for the virtual engine modeled in FIGURE 2. The fuel valves have been adjusted for individual cylinders until the peak firing pressures (PFPs) are close to equal. FIGURE 4 illustrates the air-fuel ratios needed for each cylinder, to obtain the equal PFP values of FIGURE 3. These differ by 10% between higher and lowest, which is a significant difference.

FIGUREs 2 - 4 illustrate, by using engine simulations, that achieving PFP balancing does not truly balance combustion. That is, the cylinders receive different air-fuel ratios, and although engine performance may be better than without PFP balancing, the engine performance and exhaust emissions are not optimal.

FIGURE 5 illustrates the performance of a simulated engine, specifically, pressure traces with the same air-fuel ratio in each cylinder, but with varying air manifold pressures (AMPs). Each pressure trace has a similar shape. In fact, each trace satisfies a common value for the ratio of PFP to compression pressure (CP), wherever chosen before ignition occurs.

Implicitly, FIGURE 5 illustrates the results of combustion balancing in accordance with the present invention. The target is to achieve equal air-fuel ratios for each cylinder. In other words, for each cylinder, fuel is added in an amount appropriate to that cylinder's air mass. As explained below, rather than attempt to measure the trapped air-fuel ratio, a surrogate indicator is used.

Thus, in accordance with the present invention, balanced combustion is achieved by adjusting the fuel

flow for each cylinder up or down in order to minimize the differences across cylinders in normalized peak pressure. "Normalized peak pressure" is defined as the peak firing pressure (PFP) for the cylinder divided by the compression pressure (CP) for the cylinder.

FIGURE 6 illustrates a method of cylinder-to-cylinder balancing in accordance with the invention. The method is iterative in the sense that measurements and adjustments are repeated over time until balance is achieved. Measurements can then continue or be repeated after some period of time, to ensure that the balanced combustion continues throughout engine operation.

Step 61 is measuring the peak firing pressure (PFP) for each cylinder. Step 61 may be performed by capturing a pressure trace for each cylinder, similar to the traces of FIGUREs 1 and 2. For each cylinder, its pressure trace typically represents an average of some number of cycles, such as 50 cycles, although the method could be used with a trace for a single cycle.

Step 62 is measuring the compression pressure (CP) for each cylinder. For example, the pressure at 20 degrees before TDC may be used. Any value shortly before ignition should be suitable. Like Step 61, Step 62 may be performed by averaging data over a number of cycles.

Step 63 is calculating the normalized peak firing pressure (NPFP) for each cylinder, where:

$$NPFP = PFP/CP$$

. The value for NPFP may be calculated for values of PFP and CP from a trace that has been averaged over multiple cycles or from a trace from a single cycle. The

resulting value for NPFP may be further averaged over multiple cycles or multiple groups of cycles. Both a ratio of averages or an average of ratios could be used.

Step 64 is determining a target NPFP for the engine. This "target" value is the NPFP value to which all cylinders will be adjusted. An example of a target NPFP value is the mean value of the NPFP values of all cylinders. Alternatively, a target NPFP may be specified for the engine or otherwise determined.

Step 65 is comparing the NPFP for each cylinder to the mean NPFP obtained in Step 64. If a cylinder's NPFP is equal to the target value, that cylinder is not adjusted.

Step 66 is adjusting the fuel flow into cylinders whose NPFP does not match the target NPFP value. The adjustment is based on the difference between that cylinder's NPFP and the mean NPFP. Cylinders whose ratio is below the mean are normally adjusted up, and cylinders whose ratio is above the mean are normally adjusted down. The "normally" qualification anticipates the possibility of an intelligent control algorithm that anticipates subsequent adjustments in an iterative process. A cutoff may be made for very small adjustments, and for iterative balancing, the amount of the adjustments may be limited to avoid large variations in engine operation. Steps 61 - 66 are repeated until an acceptable balance of NPFP values is obtained among the cylinders.

The adjustment of Step 66 could be manual for engines not having means for automated fuel control. In other engines, the adjustments could be made

automatically, such as by using electronically control fuel adjustment valves or injectors.

FIGURE 7 illustrates how the method of FIGURE 6 may be implemented using an interactive computer interface. The method of FIGURE 7 is appropriate as a diagnostic tool, used for engines, such as large natural gas engines. As explained below, FIGURE 7 illustrates an engine having automated fuel control, but the fuel adjustments could also be done manually.

Appropriate pressure sensors 70, one for each cylinder of engine 71, are used to obtain pressure measurements. The pressure data may be stored as a set of pressure trace data for each cylinder, similar to the plotted data of FIGUREs 1 and 2.

Computer 73 receives the pressure measurements. It stores a set of measurements from each pressure sensor, P1 - Pn.

Computer 73 is programmed to execute Steps 61 - 66. Once a fuel adjustment is calculated for a cylinder, an operator may manually adjust the amount of fuel delivered to the cylinder. Alternatively, a fuel control signal, FC1 - FCn, may be sent to engine 71 to control the fuel injector 75 for the cylinder.

A display 76 may used to provide pressure trace displays similar to those of FIGUREs 1 and 2. The traces may be used to display the PFP and CP values for the cylinders. After the calculations of Step 65, display 76 may be used to display the suggested fuel adjustment, in terms of percentage or otherwise, for each cylinder.

Pressure trace displays may be displayed for each iteration.

The system of FIGURE 7 is easily modified for embedded controller applications, rather than interactive applications. All measurements, calculations, and adjustments would then be made automatically and invisibly to the engine operator, such as in the case of the driver of an automobile. The computer would be replaced by a controller or other processor based equipment, whose functions could be integrated with other engine control operations and performed by the engine control unit.